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Effects of different polarization strategies on laser cutting with direct diode lasers

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Abstract

As *Direct Diode Lasers* are introduced as an emerging technology for laser cutting of metal sheets, new challenges arise. The relatively low beam quality remains a limitation to the maximum cutting speed. One way to balance this may be a strategic use of laser polarization in order to influence laser material interaction in the cutting kerf. In this paper the effects of cross-, linear-, radial- and azimuthal- laser beam polarization arrangements are studied with both Fusion and Flame cutting at an output power of approximately 750W. Different combinations of materials and thicknesses were cut and the maximum cutting speed and edge quality analyzed. It is found that at similar cutting edge quality, improvements in cutting speed can go up to 40% with an inert gas, such as Nitrogen, and up to 20% with a reactive gas, such as Oxygen, in agreement with analytical models for absorption previously developed by the authors.

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Keywords: Laser cutting; polarization; diode lasers; absorption; metal sheets

1. Introduction

1.1. Direct diode lasers for laser cutting of metal sheets

The interest of using *Direct Diode Lasers* (DDLs) as an alternative to more established technologies for laser processing of metal sheets, lays primarily in the increased wall plug efficiency, higher compactness and lower price per Watt that these systems can offer. The existence of different wavelengths, depending on the type of diodes used, or the possibility of having a fully polarized high power laser beam output are other important characteristics. If explored correctly, they may play an important role in the future of this technology for material processing in

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general. In recent years we have seen a growing interest from industry in this types of lasers and the application area is now expanding towards their use in laser cutting, one of the most demanding material processes in terms of beam quality. Research is closely following this trend. On one hand, developments in optics and beam combining techniques allowed considerable improvements in beam quality for conventional diode lasers (Zediker et al., 2008, Köhler et al., 2013). A first assessment of the cutting performance of such improved DDLs, when comparing with conventional lasers for cutting (CO_2 and fiber), was performed by Costa Rodrigues et al. (2014b). Further experimental results, with an overview on the theoretical benefits in terms of absorption, were described later in (Costa Rodrigues, 2014a). These results have mainly shown that industrial relevant cutting speeds, at acceptable cutting quality, are possible with such lasers. On the other hand, more ambitious optical concepts are also emerging in order to further increase the beam quality, even though, for now, in detriment of the final cost (Huang et al., 2012, Heinemann et al., 2013). These concepts have recently opened a window of opportunity in laser cutting of high reflective materials, such as copper and brass, and first experimental results were seen in the work of Previtali et al. (2015).

1.2. Polarization in laser cutting

As result of the geometric design of the laser cavity, most high power CO_2 laser sources are, originally, linearly polarized. In this condition the cutting is dependent on the cut direction, and known to positively influence the cutting speed in the direction of polarization (Powell, 1998). Nevertheless, a phase retarder mirror is typically used to obtain circular polarization, axisymmetric by nature, to avoid this dependence and obtain homogeneous cuts. Niziev et al. (1999) and Nesterov et al. (2000) first noticed the potential of using the polarization in benefit of the cut process when they modeled the effect of several polarization strategies on cutting efficiency. They pointed out radial polarization, also axisymmetric, as the most interesting polarization state for cutting with a 10 μm wavelength laser. It was predicted to be up to 1.5 to 2 times more efficient in terms of achievable cutting speed than commonly used circular polarized lasers. These predictions were only experimentally proven correct some years later by Abdou Ahmed et al. (2007), as they became capable of generating a high power radial polarized CO_2 laser beam using an intracavity resonant granting mirror. The same research group has also invested in obtaining a radial polarized output from 1 μm radiation (Weber et al., 2011), in this case a high power disk laser, using an extra-cavity polarization conversion mechanism. The input laser is required to be linearly polarized and, thus, a first step to polarize the laser, that typically wastes a considerable amount of power, is needed. Even without an efficient way to obtain high power lasers with a radial polarization output, research has been dedicated towards it for 1 μm radiation and shown a possible increase in edge quality and process speed (Hirano et al., 2012). More recently, new investigations on cutting with polarized DDLs have shown that an optimized polarization strategy may considerably improve cutting efficiency, with up to 40% difference in cutting speed for fusion cutting (Costa Rodrigues, 2016).

This paper builds on previous studies from the authors on polarization control with direct diode lasers (Costa Rodrigues, 2016), and looks to a number of polarization strategies and their influence on laser cutting of metal sheets. Fig. 1 shows the absorption graph of 1 μm radiation on steel, and a schematic representation of the expected absorption for the different polarization strategies discussed in this paper. These assumptions will be later discussed in the conclusion section of this paper. Laser cutting with a reactive gas, flame cutting, will be explored further by introducing cutting results with a linearly polarized strategy. A considerable improvement in cutting speed is visible, in comparison with previous cutting results with an approximately azimuthal and radial polarization strategies. Furthermore, fusion cutting experiments are enhanced by adding new experimental results and are discussed. This includes different polarization strategies combined with two types of materials, namely stainless steels type 304L and 316L.

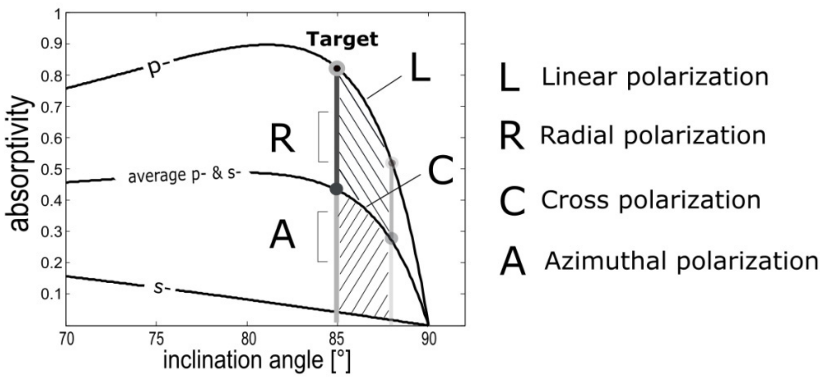


Fig. 1. Schematic representation of the position of the studied polarization strategies on a laser absorption graph in function of inclination angle. Data gathered from the model described in (Costa Rodrigues et al., 2014a, Costa Rodrigues et al., 2016).

2. Description of test setup and experiments

2.1. Test setup

The experiments described below were carried out using two DDL sources, with an output power of 750 W, installed in an experimental gantry platform that allows an independent control of common cutting parameters such as focal point position, stand-of-distance, nozzle opening, gas selection and gas pressure. The polarization strategies described in Table 1 were obtained using different combinations of optics and optical designs. Cross-polarization (C) is typically the output of a conventional high-power diode laser. In this case, polarization coupling is used as one of the combining techniques to scale up the power while maintaining beam quality. In order to obtain a linearly polarized output with the same power and beam quality, wavelength coupling can be used instead. This technique produces a laser beam with more than one wavelength. Both radial (R) and azimuthal (A) strategies are obtained from the linearly polarized laser source. In this case a beam converter, composed of a combination of segments of beam retarders, is used in order to locally rotate the polarization of the laser beam. Four segments were used to approximate these polarization states, defining a total of four axes of symmetry. It is important to notice that the beam quality obtained for the C- module is slightly better than the one obtained for the other three setups. This is mainly attributed to different diode bars and optical components used in the two DDL sources.

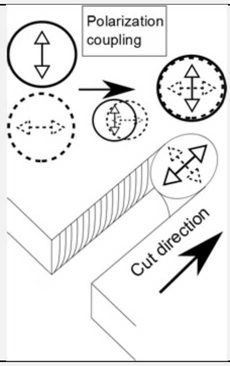
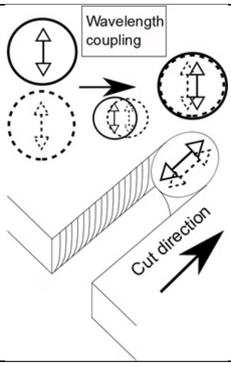
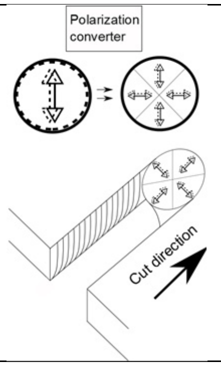
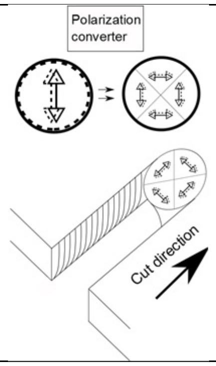
2.2. Flame cutting experiments

These tests were performed for the L- polarization strategy in the exact same conditions as the tests described in (Costa Rodrigues, 2016), where R- and A- strategies were tested. Oxygen at 99.95% purity (Oxygen 3.5) was used to cut 4 mm thick S355 structural steel. The material composition is given in Table 2. A stand-of-distance of 1 mm and a conical nozzle with an opening diameter of 1.5 mm were selected. Five focal point positions and three gas pressure levels were used: low pressure (0.5 bar); medium pressure (1 bar); and high pressure (1.5 bar); in order to control the energy input to the process. Cutting speed steps of 200 mm/min were used for each experiment, from 1400 to 2600 mm/min.

2.3. Fusion cutting experiments

In these experiments, the L- polarization strategy is compared with the cutting results obtained with both R- and A- polarization strategies in (Costa Rodrigues, 2016). The cutting tests are intended not only to understand the effects of different polarization strategies for an inert gas process, but also to attest the possible combined influence with different types of stainless steels. For that purpose Nitrogen 5.0, with a purity of 99.999%, was used to cut 3 mm thick stainless steel sheets of both 304L and 316L types (material composition: see Table 2). Each test consists of cutting a line with gradually increasing cutting speed till failure. For the performed set of tests, the failure condition was clear and corresponded to an incomplete cut through with molten material emerging from the top surface. The speed is increased in steps of 50 mm/min. Gas jet parameters were kept constant at a semi-optimized level: stand-of-distance of 1 mm, nozzle opening of 1.5 mm and gas pressure of 16 bar.

Table 1. Full description of polarization strategies.

Laser beam designation	Cross-polarization	Linear-polarization	Radial-polarization	Azimuthal- polarization
Abbreviation in text	C-	L-	R-	A-
Setup descriptive scheme				
Symmetry axes	4	2	4	4
Base BPP	22 *mm mrad*	22 *mm mrad*	22 *mm mrad*	22 *mm mrad*
Measured BPP[1]	28,39 *mm mrad*	33,58 *mm mrad*	32,85 *mm mrad*	30,78 *mm mrad*
Beam waist[1]	374 *µm*	414 *µm*	414 *µm*	440 *µm*
Wavelength	920 *nm*	920 & 960 *nm*	920 & 960 *nm*	920 & 960 *nm*
Output power	750 *W*	750 *W*	740 *W*	740 *W*

1 measurements performed with 2nd moment algorithm according to ISO 11146

Table 2. Material composition of the metal sheets used in the experiments.

Steel	C%	Mn%	P%	S%	Si%	Fe%				
S355 [1]	0.23	1.60	0.05	0.05	0.05	Balance				
Stainless	**C%**	**Mn%**	**P%**	**S%**	**Si%**	**Cr%**	**Ni%**	**Mo%**	**N%**	**Fe%**
304 L [1]	0.03	2.00	0.045	0.03	0.75	18.00-20.00	8.0-12.0	-	0.1	Balance
316 L [1]	0.03	2.00	0.045	0.03	0.75	16.00-18.00	10.00-14.00	2.00-3.00	0.1	Balance

[1] Typical composition from supplier catalogues

3. Results and discussion

3.1. Flame cutting experiments

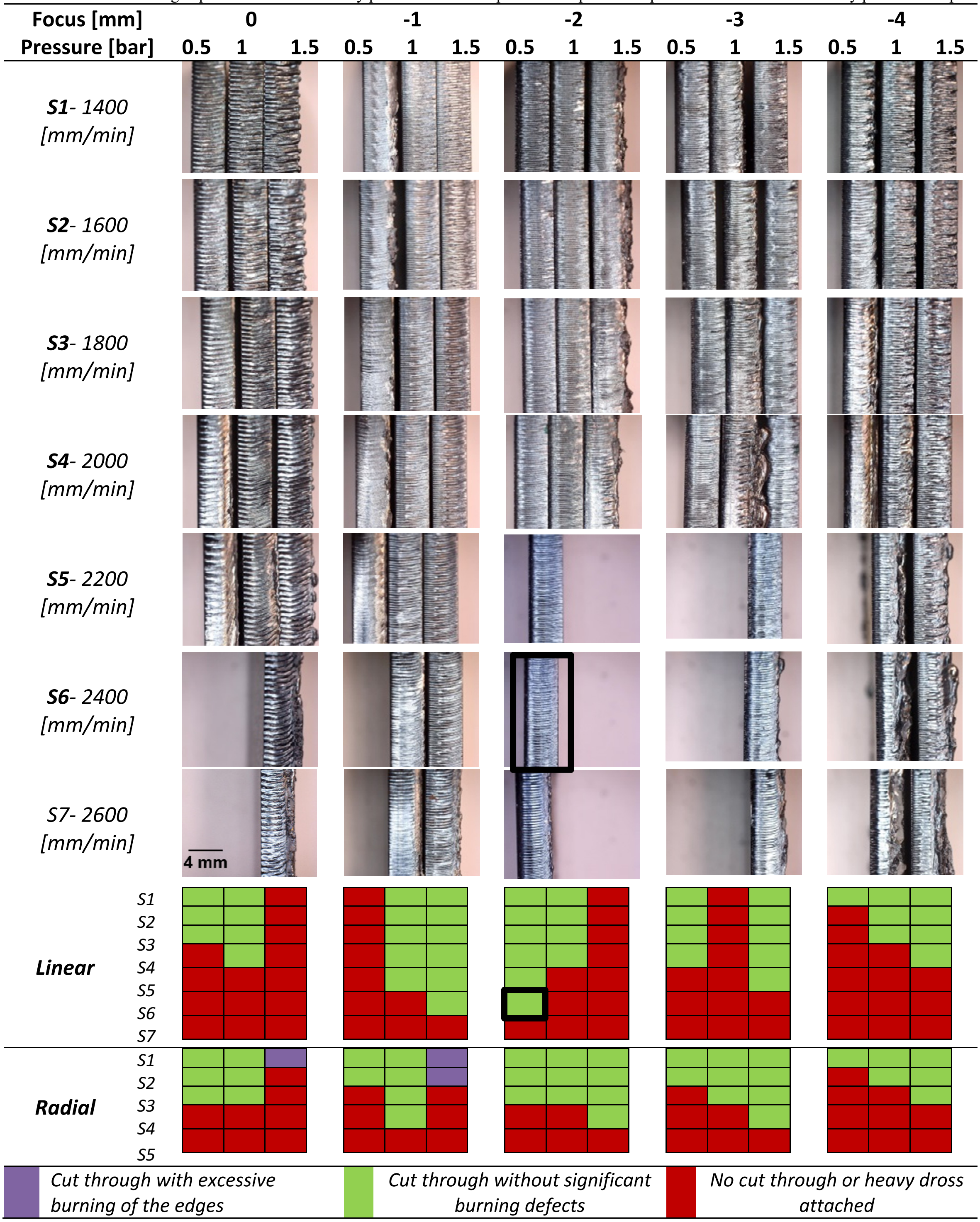
The results of the flame cutting experiment are depicted in Table 3. Regarding the focal point position, it is clear that, when positioned at the top surface (left column in the table), deep striations are formed independently of gas pressure or speed. At a lower position the striations became less deep and the edge quality improves considerably. When the focal point is positioned even lower, close to the bottom, an excessive waviness of the bottom part of the edge surface is visible, suggesting the existence of a different mechanism during the cutting process. This pattern is similar to what is observed for both R- and A- polarization in previous research (Costa Rodrigues, 2016). The effect of pressure and the observed maximum achievable cutting speed are different though. The color codes, used in the lower part of the table for the experimental results, document the qualitative assessment of the cutting results. The best cutting condition is considered for a combination of high speed and an acceptable edge quality, which is characterized by a relatively smooth edge and no attached dross. In the present case, a condition that allows a maximum cutting speed of 2400 mm/min and an acceptable edge quality was found and is marked by the black box in this table. For a similar edge quality, this corresponds to a 20 % higher cutting speed when compared to a maximum of 2000 mm/min achieved with the R- strategy. Other important aspect is the fact that the cutting process seems to be less stable regarding the gas pressure levels. We see that considerably more experiments failed for the whole range of speeds for the L- strategy. This could be related to strong asymmetries between the absorbed laser in the cut front and on the cut sides. Other aspect worth noticing is the fact that excessive burning of the edges was not seen in the L- strategy experiments. This was characterized by much degraded cut edges due to excessive energy in the process. This occurred mainly at low cutting speeds and higher gas pressures.

3.2. Fusion cutting experiments

The results of these experiments are summarized in Fig. 2. It is important to notice that no clear relation seems to exist between the cutting speed and the amount of dross attached. In this case the optimal condition regarding cutting speed is selected to be in the closest successful cut interval before failure. These maximum cutting speeds are given in Fig. 2a for the different combinations of focal point, material and polarization strategy used. The dross formed, however, seems to be dependent mainly on the focal point position. Three classes of cut could be clearly defined: Class I for no visible dross attached or the presence of small grains of molten material only; Class II as the amount of grains is too high and/or small dross is formed; and Class III when heavy dross remains attached. Fig. 2b, c and d are representative of these conditions. We see that the highest maximum cutting speeds, for each polarization strategy, are not coincident with the best cutting quality edges, and are obtained when the focus is positioned near the center of the sheet. The maximum cutting speeds achieved with the L- strategy are the highest for the whole range of focus positions considered. As expected, with the A- strategy the cutting speeds are considerably lower, especially in a region of Class I and Class II, where the focal point is positioned closer to the bottom. In the class III region this difference becomes less significant and the speeds are similar to the R- strategy. The curve for the C- strategy is given here only as reference since these cutting tests were performed on a 304 L sheet from a different manufacturer. Nevertheless, as expected from the initial assumptions from the absorption curves, it is possible to see that this curve is positioned in between the A- and R- strategies in the Class I region. The significant decrease in cutting speed for the C- strategy at a higher focus position may be related to a slight different material composition and to the relatively different beam geometry in comparison with the other three strategies.

Important to notice is the fact that the trends observed for the maximum cutting speeds, with the studied polarization strategies, seem to be similar for both the 304L and 316L materials. In all three cases the 316L curve consistently shows a higher cutting speed. Nevertheless, this relatively steady shift may be explained with a closer look to the material properties. The 316L type of stainless steel has typically a lower melting point, in the range between 1375 °C and 1400 °C, when compared to the 304L type, with a range between 1400 °C and 1450 °C, which is directly linked to the different material composition (Peckner et al., 1977). As other properties, such as specific heat, conduction or density, do not change significantly (Peckner, 1977), we may consider that the extra energy needed during the cutting process, due to the higher melting point, is the probable cause of a lower cutting speed for the 304L samples.

Table 3. Flame cutting experiments with a linearly polarized beam output and comparison of process window with a radially polarized output.



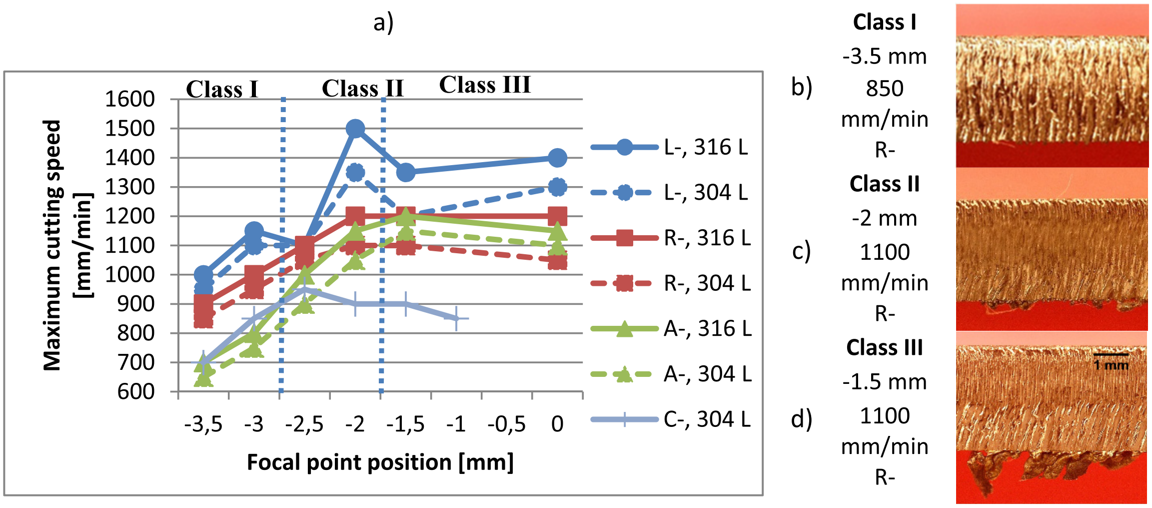


Fig. 2. Results for the fusion cutting experiments: (a) maximum achievable cutting speeds for different focal point positions, materials and polarization strategies; (b),(c) and (d) cutting edge pictures representative of the amount of dross in each quality class.

4. Conclusions

The results presented in this paper are ultimately demonstrating the potential of an optimized polarization strategy for increasing performance of cutting with DDLs. Both flame and fusion cutting processes could greatly improve from it, even though to a different extent. In general, it can be observed that flame cutting with an L-strategy could be up to 20% faster than both A- and R- strategies. On the other hand, without the extra energy provided by the exothermic reaction, due to the oxygen assist gas, this relative difference increased. Here, we also saw a clear difference between A- and R- strategies, with the best performance obtained for the latter, as initially predicted by analytically calculated absorption curves. Nevertheless, the maximum cutting speeds were once again observed for the L- strategy, up to 40% higher depending on cutting conditions.

Practically, it is important to notice that the L- strategy is not axis-symmetric and that the A- and R- strategies are just approximations of real azimuthal and radial polarized laser beams. The principle used for the beam converter relies on a total of four polarized divisions within the laser beam cross section. With an increase of the number of such divisions, it would be expected that the performance obtained by the R- strategy would also increase, getting closer to what observed for the L- strategy. As we look back to the absorption graphs in Fig. 1 and combine it with the cutting results presented here, this idea becomes clear. This would, however, increase the complexity of the beam converter. A different option would be the use of an indexing laser head capable of guiding the polarization of the L- strategy. Eventually, a tradeoff between increasing cutting performance, complexity of the beam converter or designing an indexing head concept would need to be considered.

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